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The impacts of ventilation strategies and facade on indoor thermal environment for naturally ventilated residential buildings in Singapore

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Abstract

The impacts of various ventilation strategies and facade designs on indoor thermal environment for naturally ventilated residential buildings in Singapore are investigated in this study based on thermal comfort index. Four ventilation strategies, nighttime-only ventilation, daytime-only ventilation, full-day ventilation and no ventilation were evaluated for hot-humid climate according to the number of thermal discomfort hours in the whole typical year on the basis of a series of TAS simulations. Parametric studies of facade designs on orientations, window to wall ratios and shading devices were performed for two typical weeks by coupled simulations between building simulation ESP-r and CFD (FLUENT). The results indicate that full-day ventilation for indoor thermal comfort is better than the other three ventilation strategies. With various facade design studies, it was found that north- and south-facing facades can provide much comfortable indoor environment than east- and west-facing facades in Singapore. It is recommended that optimum window to wall ratio 0.24 can improve indoor thermal comfort for full-day ventilation and 600 mm horizontal shading devices are needed for each orientation in order to improve thermal comfort in further.

Keywords: Natural ventilation; Ventilation strategies; Facade design; Coupled simulations

1. Introduction

With the emergence of energy shortages, climatic changes and sick building syndromes associated with the common usage of air-conditioning, authorities have recognized the necessity in finding strategies that can cultivate a more sustainable design in line with satisfactory indoor thermal comfort. Without doubts, natural ventilation can be an appropriate solution for these deteriorating problems. In fact, the idea of natural ventilation has already been accepted by people and designers in Singapore since 86% of the population is living in Housing Development Board (HDB) flats, which are designed to be naturally ventilated. Although the concept of natural ventilation is not complicated, it is a challenge to design naturally ventilated buildings as natural ventilation is difficult to control.

The achievement of indoor thermal comfort in naturally ventilated buildings is determined by the thermal performance of facade to a large extent, ranking second to the local climatic characteristics. Although Singapore is situated on the 1.2° latitude with relatively high temperature ranging from 23 to 34 °C and high relative humidity averaging 84% for the whole year, the high probability of achieving comfortable indoor environment with natural ventilation was investigated and reported [27]. We may not have choices for the local climate conditions (solar radiation, humidity, air temperature, wind speed, etc.), which are determinative for the feasibility of natural ventilation in certain regions, successful facade designs by architects and engineers, including the thermal property of construction materials, window sizes, shading, and building orientations, and effective ventilation strategies can provide an optimum modifier to achieve better indoor thermal comfort with minimum energy usages. Several research works are investigated on the impacts of facade components on energy consumptions in sealed mechanically ventilated buildings (e.g. [3,5,18,22]). However, the

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knowledge of facade designs in naturally ventilated building is deficient, especially for the hot-humid climate.

2. Literature reviews

2.1. Ventilation strategies

With the increase of indoor air velocity, neutral temperature for naturally ventilated buildings could be increased [11]. Graca et al. [12] used a coupled model of computational fluid dynamics (CFD) and building thermal analyses to simulate heat transfer and airflow in the apartments in Beijing and Shanghai. Two passive cooling strategies, daytime ventilation and night cooling have been evaluated based on occupant's thermal comfort. Sreshthaputra et al. [25] coupled DOE-2 and 3D transient CFD simulations for an unconditioned 100-year-old Buddhist temple in an urban area of Bangkok, Thailand. Several remedial changes for improving poor indoor thermal conditions include applying a low absorption roof coating, adding ceiling insulation, increasing the sunshade at the building's exterior surfaces and nighttime-only ventilation.

2.2. Construction material properties

The study of heat gains through facade for naturally ventilated buildings is more critical than that for air-conditioned buildings since the amount of heat gains is a significant factor influencing the indoor thermal comfort. Building design and comfort study in Bangladesh by Mallick [19] indicated rooms with thicker walls tend to be more comfortable, particularly in the hot and dry period between March and June. In Singapore, the current facade construction material standard for air-conditioned buildings is envelope thermal transfer value (ETTV), which should not exceed $50\,\mathrm{W/m^2}$ [2]. However, for naturally ventilated buildings in Singapore, there are no clear facade design guidelines. Building regulations in Singapore [23] only specify that the U-value of any external wall in non-air conditioned building should not be more than $3.5\,\mathrm{W/m^2\,K}$. Wong [31] investigated the effects of U-value of construction materials for naturally ventilated buildings in Singapore. It was recommended that U-value for the east- and west-facing facade should be no more than $2\,\mathrm{W/m^2\,K}$ and for north and south should be no more than $2.5\mathrm{W/m^2\,K}$. However, in the study, the effects of WWR on indoor air velocity for naturally ventilated buildings are not considered.

2.3. Window sizes

Ventilative cooling, by means of convection using surrounding air as a heat sink, has been used in hot-humid locations where ventilation can make summers without air conditioning at least more tolerable if not perfectly comfortable. Wind-driven ventilation characteristics through opening have been studied by several researchers [7,14,16,20,24]. Tantasavasdi et al. [26] explored the potential of using natural ventilation as a passive cooling system for new house designs in Thailand. The study found that it is possible to use natural ventilation to create a thermally comfortable indoor environment in a house in a Bangkok suburb during 20% of the year. The inlet aperture area should be around 20% of the floor area to achieve adequate natural ventilation for an acceptable comfort level.

2.4. Shading devices

Appropriate external shading devices can control the amount of solar radiation admitted into the room, which could largely reduce cooling loads and improve indoor thermal comfort and day lighting quality. Muniz [21] investigated the effect of external shading devices on day lighting, airflow pattern and thermal comfort for tropical hot-humid climate via a low-speed wind tunnel and an artificial skydome. Bouchlaghem [4] presented a computer model, which simulate the thermal performance of the building taking into account design variables related to the building envelope and optimize window-shading devices with optimization programs. Corrado [6] used Ombre software to evaluate the influence of the geometry of window-shading device system on the thermal performance.

Based on the above literatures, there are very few studies on facade designs to improve indoor thermal comfort for naturally ventilated buildings, especially for hot-humid climate. In addition, it is noticed that there are very few guidelines for facade designers of naturally ventilated buildings or for occupants with operation of individual control over their thermal environment for the hot-humid climate. Therefore, it is important to conduct this research on ventilation strategies and facade designs in Singapore to help architects to design naturally ventilated buildings with good interior thermal comfort based on the local climate.

3. Evaluation criteria for ventilation strategies and facade designs

Facade designs for natural ventilation is a challenging task, which is related to indoor thermal comfort and domestic energy consumption. There are several important facade design parameters. However, it would probably be biased to simply take one parameters into account and neglect others. Thermal comfort can be used as the criteria to evaluate ventilation strategies and the combination effect of different facade design parameters.

Accurately predicting thermal comfort for naturally ventilated building, which is quite different for air-conditioning spaces because of various thermal experiences, changes in clothing, availability of control and different occupant expectations [1] is still in the discussion stage.

An extension of the PMV model that includes an expectancy factor was put forward for use in non-air-conditioned building [10]. The new adjusted PMV model [10] is to multiple the predicted PMV values [9] with expectancy factors (0.7 for Singapore).

Humphreys and Nicol [17] found that in the surveys of individual buildings, use of PMV in ISO7730 can produce substantial bias for predicting thermal comfort for naturally ventilated and air-conditioned spaces. One adjusting PMV model has been put forward for both naturally ventilated buildings and air-conditioned buildings.

ASHRAE Standard [1] provided the alternative method to predict acceptable thermal conditions for naturally conditioned spaces and thermal responses in naturally ventilated space are linked with the outdoor climate. The estimation of thermal comfort using this method is limited with mean monthly outdoor air condition.

Thermal comfort studies for naturally ventilated buildings have been carried out in National University of Singapore. Feriadi [11] developed a thermal comfort prediction chart and fuzzy thermal comfort model suitable for naturally ventilated buildings in the tropics based on 1063 data collected through field surveys in Singapore and Indonesia. Wong and Khoo [30] did a field study in classrooms in Singapore, which were mechanically ventilated by fans. The results further confirmed that the ASHRAE standard 55 is not applicable in free-running buildings in the local climate. The adjusted PMV model by Fanger and Jorn Tofttum [10], which incorporates two common forms of adaptation: namely, reducing activity pace and expectation, still showed discrepancy in predicting actual thermal sensations, especially at lower temperatures. Thermal comfort regression model [27] for naturally ventilated residential buildings has been derived from 538 field survey data in Singapore

$$\mathrm{PMV} = -11.7853 + 0.4232 \times \mathrm{Temp} - 0.57889\,V \qquad (1)$$

where Temp (°C) indicates the indoor air temperature and V (m/s) refers to indoor air velocity measured at 1.2 m above the ground. The term PMV refers to the average (mean) response of a group exposed to a given climatic conditions rather than individual responses. As relative humidity is highly correlated with dry bulb temperature, the impacts of variation of dry bulb temperature on thermal comfort can indirectly indicate the effects of relative humidity changes on thermal comfort. In another aspect, relative humidity in hot-humid climate is always in the high level (above 60%). Therefore, the parameter relative humidity is not involved in the regression model. clo and met are normally standard for residential buildings in Singapore. clo is around 0.34–0.5 as people tends to adjust their clothes at home for better thermal comfort and met is equal to 1.0. Dry bulb temperature and air velocity are parameters for thermal comfort prediction. The acceptable thermal condition can be achieved within the −1.3 and 1.1 data [11]. Therefore, the upper limit of indoor discomfort is set to be PMV = 1.1. In this study, the regression model (Eq. (1)) is used for the evaluation of indoor thermal environment with different ventilation strategies and facade designs.

4. Ventilation strategies

4.1. Methodology for ventilation strategies

Four different ventilation strategies with the combination of various construction materials for naturally ventilated buildings are investigated for hot-humid climate in Singapore by TAS building simulation software [8]. TAS is a suite of software products, including TAS Building Designer, TAS system and TAS Ambiens to simulate the dynamic thermal performance of buildings and HVAC systems and trace the thermal state of the building through a series of hourly snapshots, with integrated zonal simulation of natural and forced airflow.

In order to find the most effective ventilation strategy for natural ventilation in hot-humid climate, the impacts of different ventilation strategies for natural ventilation, including daytime ventilation, nighttime ventilation, full-day ventilation and no ventilation (1 ach infiltration) on indoor thermal environment were investigated. The outdoor averaged temperature and solar radiation profiles in the typical year of Singapore are summarized in Figs. 1 and 2. Considering the solar radiation and outdoor temperature profile, the night ventilation is scheduled from 6pm to 7am. Natural ventilation for the rest of the time is

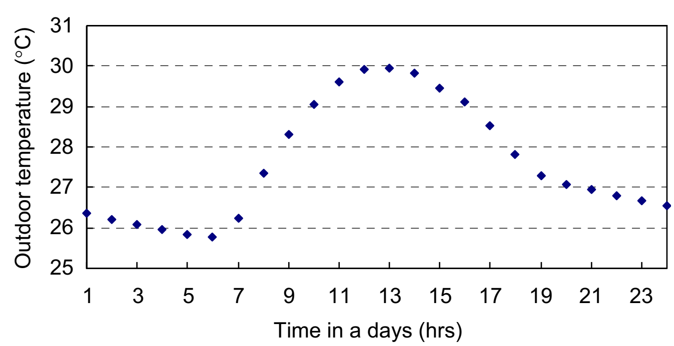

Fig. 1. Outdoor average temperature profile in the whole year.

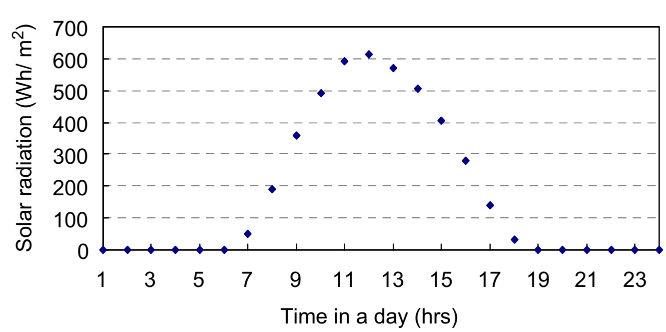

Fig. 2. Outdoor average solar radiation profile in the whole year.

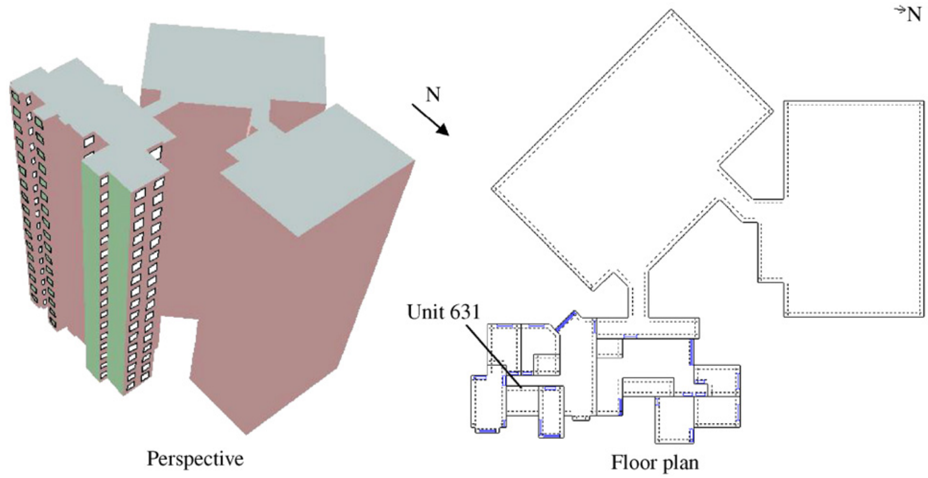

Fig. 3. HDB 988A geometric model in TAS simulation.

considered as daytime ventilation. Various ventilation strategies including no ventilation, daytime ventilation, all day ventilation and nighttime ventilation have been compared on the basis of the number of thermally unsatisfactory hours for the whole year.

Air change rate (ACH) obtained from TAS simulations for air velocity near the window (V) calculation. The averaged indoor air velocity is obtained from Eq. (2).

$$V(\mathrm{m/s}) = \frac{\mathrm{ACH} \times \text{Volume of room}}{\text{Section area} \times 3600}. \quad (2)$$

4.2. The simulated building for ventilation strategies

For the investigation on ventilation strategies, the HDB Block 988A located in Jurong west in Singapore, a typical residential building, was modeled by the TAS simulation. The residential building is 18-storeys with 6 units per floor with different orientations. The geometric model of the residential building (Fig. 3) has been built in TAS software to carry out the parametric simulations on thermal comfort for naturally ventilated buildings in the whole typical year of Singapore. East-facing master bedroom in the unit 631 has been chosen to be the subject for simulations since east- and west-facing facade receive much more solar radiation than north- and south-facing facades in the tropical regions. The geometric data for the master bedroom is summarized in Table 1. The construction material of the external wall is 100 mm foamed concrete block wall with 25 mm plaster on both sides. Thermal conductance of the construction material is 1.054 $\mathrm{W/m^2\,K}$ with 5.4 h of time constant. Absorptance for solar radiation for both internal and external opaque surface is 0.4, and emittance for thermal radiation for both surfaces is 0.9. Internal heat sources such as equipments, lighting and occupants in the unit have been ignored.

Table 1
Geometric data for master bedroom in TAS model

Item	Dimensions (m)	Characteristic
Floor to floor height	2.8	
East facing window	1.2 × 1.5	Fixed close
West facing window	1.2 × 1.2	Open/close
North facing window	1.2 × 0.6	Open/close
Internal door	2 × 0.9	Close

4.3. Building simulation results for ventilation strategies

Different ventilation strategies with the variation of construction materials were simulated. In total, 56 cases have been investigated in the simulations. The four ventilation strategies: no ventilation, daytime ventilation, nighttime ventilation and full-day ventilation strategies have been parametrically studies with 14 types of material properties with the variation of thermal conductance ranging from 0.174 to 2.909 $\mathrm{W/m^2\,K}$ and time constant ranging from 0 to 60.8 h. Thermal conductance determines the heat flow in unit time by conduction through unit thickness of a unit area of the material, across a unit temperature gradient. Under the condition of fluctuation, when the structure is heated and cooled periodically as a result of variation in outdoor temperature and solar radiation, the heat capacity has a decisive effect in determining indoor thermal conditions. Time constant is the function of thermal resistance and thermal capacity. Thermal inertia, indicating longer time constant, is defined by volumetric heat capacity multiplied its conductivity. Actually, thermal conductance and time constant in real buildings vary in certain ranges. In order to track general trends of the variation of thermal discomfort hours, some extreme cases are also calculated, for example 600 mm foamed concrete external wall with 25 mm plaster on both sides (time constant 60.8 h and thermal conductance 0.396 $\mathrm{W/m^2\,K}$).

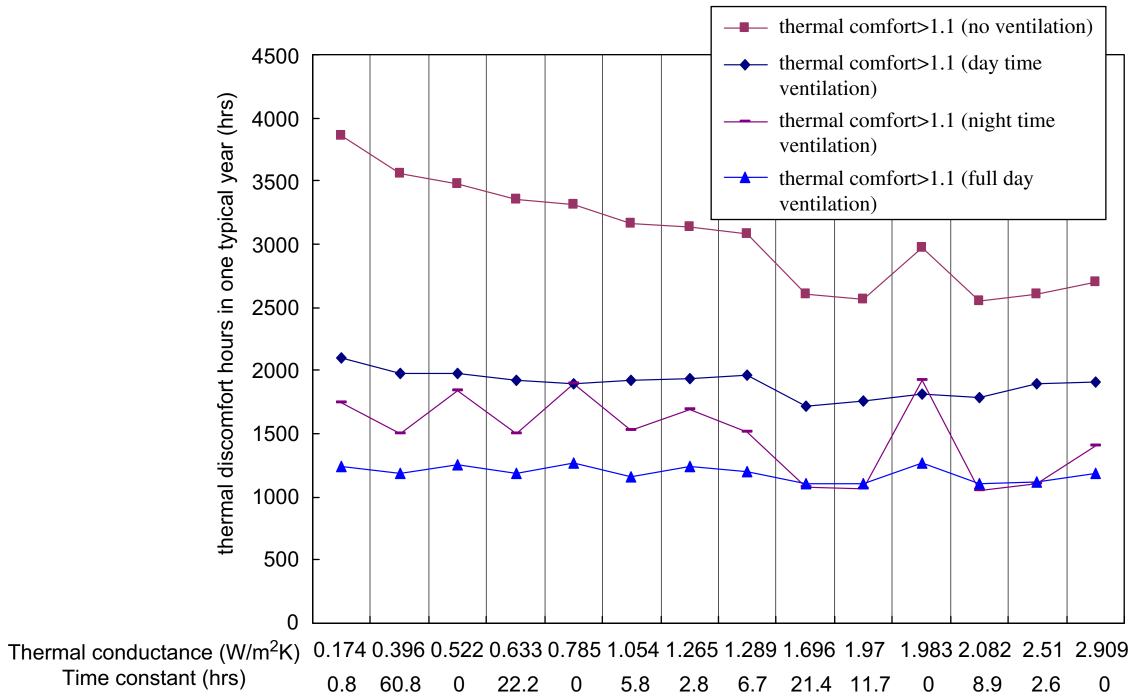

Fig. 4. Thermal discomfort hours profile with various material properties with four.

Thermal discomfort hours in the whole typical year based on thermal comfort model in Singapore for naturally ventilated buildings for all the 56 cases have been shown in Fig. 4 with various ventilation methods. When the PMV scales are more than 1.1, the index indicates that the objective conditions inside the building tend to give occupants the feeling of uncomfortably warmth, which is in the range of warm feeling. The ventilation strategies and material properties are interactively implemented to study the impacts on indoor thermal environment.

In the perspective of material properties, it can be concluded that construction materials with strong insulation, either with higher mass inertia (longer-time constant) or lower mass inertia (shorter-time constant), is not suitable for Singapore with hot-humid climate, while non-insulated construction materials with about 2 W/m^2 K and fairly thermal mass inertia are wise choices for naturally ventilated buildings in Singapore. Material properties, especially thermal conductance, under the condition of no ventilation have strong relationship with indoor thermal comfort. With the increase of thermal conductance of construction materials, thermal discomfort hours are decreasing, except high heat conductance with little thermal mass inertia. However, the impacts of material properties on indoor thermal comfort are not obvious when room ventilation is effective. There are very narrow variations in the case of full-day ventilation with the changes of material properties, although the tendency of the profile is consistent with others.

From the aspect of ventilation strategies, full-day ventilation, which generally has the smallest unsatisfactory hours among the four ventilation strategies, is the most effective strategy for thermal comfort in Singapore. No ventilation shows the worst performance of buildings that most time in the year it is in the slightly warm zone. The results indicate that ventilation is an effective strategy for thermal comfort. Night ventilation is more effective than daytime ventilation since temperature in the nighttime normally is low enough to provide thermal comfort, while diurnal temperature is generally 7–8 °C higher than nocturnal highest temperature and solar heat gains in tropic region are quite significant in the daytime. Night ventilation is not as effective as full-day ventilation with low thermal conductance or little thermal inertia. Nevertheless, proper thermal properties support ventilation effectiveness. With good heat conductance and fairly thermal inertia, indoor conditions with night ventilation are slight better that those with full-day ventilation.

In addition, the impacts of the east-facing window (window to wall ratio of 18.9%), which is closed on thermal comfort have been tested. All the other two windows inside the room are fully opened. Three scenarios under full-day ventilation strategy, without window, with opened window, and closed window, have been investigated with external wall of 2.082 W/m^2 K in thermal conductance and 8.9 h in time constant. The results indicate that the design of closed window is the worst case, which has about 100 h discomfort hours in a year more than those of the other two cases. Therefore, the closed window for day lighting, especially on the orientation of high solar radiation intensity, should be avoided in

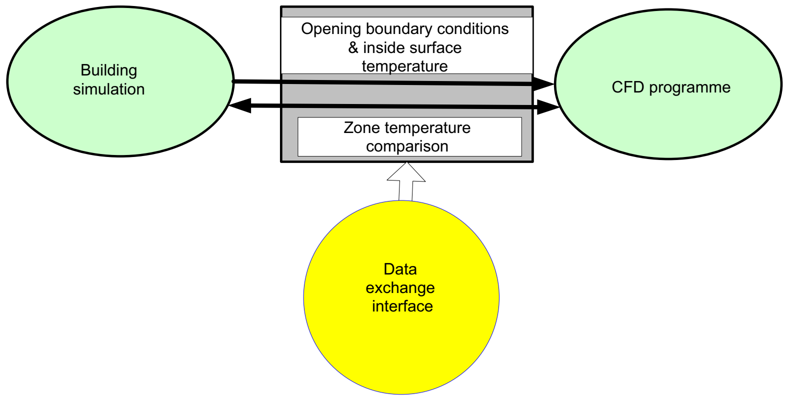

Fig. 5. The coupling strategy between building simulation and CFD.

the designs of naturally ventilated buildings for better indoor thermal environment.

5. Various facade design evaluations

5.1. Methodology for facade design evaluations

For more accurate prediction of indoor thermal environment for naturally ventilated buildings as building simulation assume the zone is well mixed, coupled simulations [28,29] between building simulation (ESP-r [13]) and indoor CFD simulation (FLUENT [15]) were adopted in this parametric study. Three prominent facade design parameters, including orientations, window to wall ratios and shading device dimensions, were investigated with a series of coupled simulations.

The newly developed coupling program between ESP-r and FLUENT for natural ventilation prediction, providing a fast and accurate method to assess the performance of natural ventilation in whole buildings, as well as detailed thermal environmental information in some particular spaces, has been used for facade evaluations. The procedure of this coupling process, as shown in Fig. 5, is to obtain the internal surface temperature, pressure at the openings, which will be saved at data exchange interface. By using the script program from the interface, the boundary conditions will be automatically fed into indoor CFD simulation for a series of hours. With the aids of developed coupling program, coupled simulations between building simulations and computational fluid dynamics can quickly and accurately predict indoor thermal environment for long-term or short-term natural ventilation studies. The data exchange interface has been programmed to automatically implement the data exchange between the two programs. Thermal comfort regression model (Eq. (1)) for indoor environment is provided for evaluation of various facade designs based on the generated results.

In this study, indoor thermal environment with various facade designs based on thermal comfort index on the aspects of window to wall ratios, shade devices and orientations are appraised in two typical weeks.

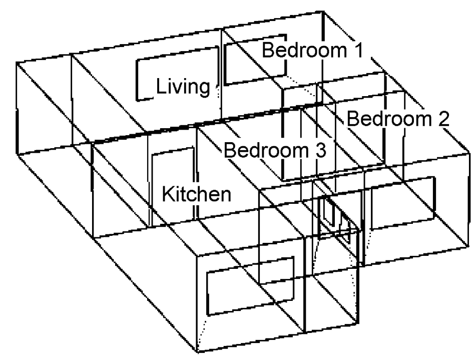

Fig. 6. The layout of the four-room HDB unit.

5.2. The simulated building for various facade designs

HDB building block601, west coast, is used for the facade design study and a typical living room in the HDB residential buildings on the sixth floor, which holds one external wall, is the targeted subject in this parametric study. The layout of the HDB unit is shown in Fig. 6. The living room has five openings: one window within the facade, one door connected with kitchen and the other three doors are connected with bedroom1, bedroom2 and bedroom3, respectively. The window and door connected with kitchen are assumed to be fully open and the other three doors connected with bedrooms are assumed to be close. The window within the facade in kitchen is assumed to be fully opened for 24 h.

5.3. Demonstration of simulation results with coupling program

With coupled simulations, indoor thermal environment can be predicted in details. The results for an hour case with the aids of the coupling program are shown here for demonstration. It is 9 AM on 18th May with the ambient temperature of 30.7 °C and wind direction 77° and wind speed of 1.4 m/s. The demonstrated facade design case is east-facing room with window to wall ratio 0.24 and no

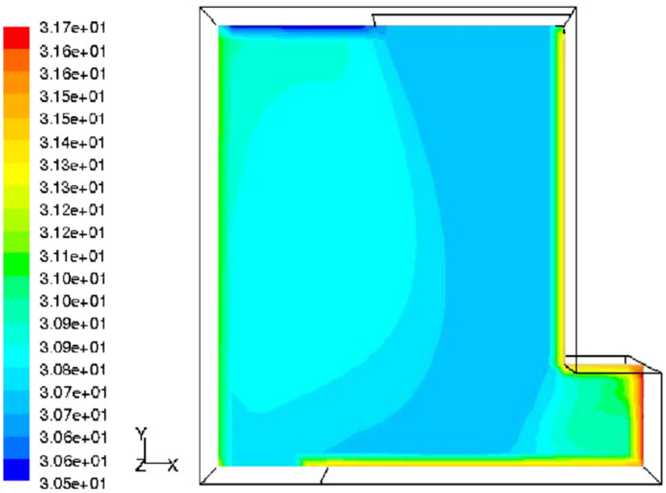

Fig. 7. Contour of indoor temperature (°C).

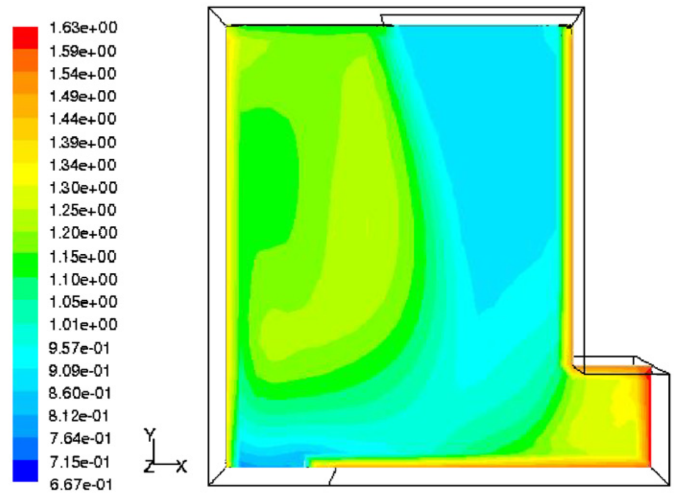

Fig. 10. Contour of PMV (indoor thermal comfort index).

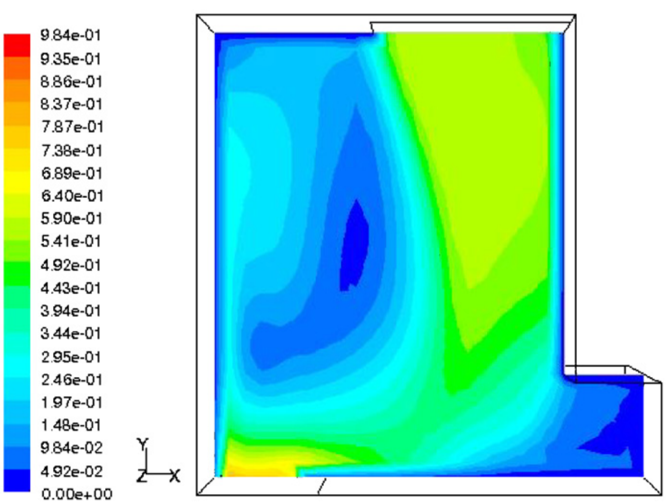

Fig. 8. Contour of indoor velocity magnitude (m/s).

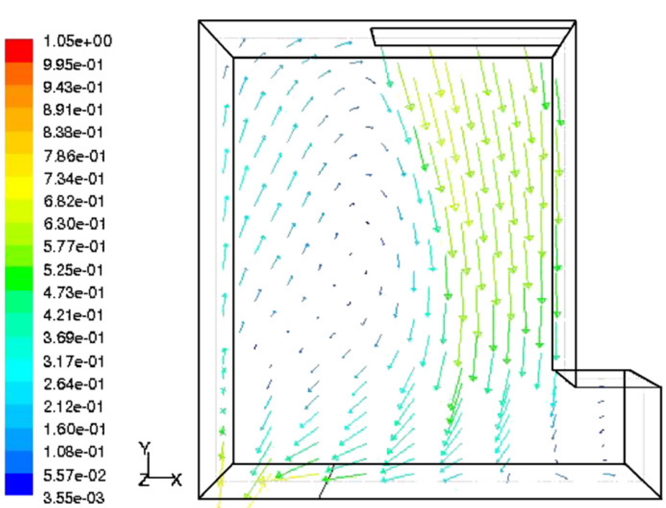

Fig. 9. Velocity vectors colored by velocity magnitude (m/s).

shading device. Figs. 7–10 illustrate detailed indoor temperature, velocity magnitude, velocity vector and PMV index of the living room 1.2 m above the floor, respectively. From the PMV index in Fig. 10, it can be seen that indoor thermal comfort are non-uniform and the area with higher air velocity provides better indoor thermal comfort than the stagnant spaces.

5.4. *Thermal comfort evaluation by two typical weeks*

Two typical weeks in May (dry season) and October (raining season) are selected to test for thermal comfort with various facade designs. From the climatic data analysis in Singapore [27], the largest percentage of thermal discomfort in the typical year appears in the month of May for Singapore. The choosing of typical week in the month is outlined as follows:

(a) The number of instances where the global radiation, dry bulb temperature, and wind speed in a particular hour in the week exceeds the maximum or falls below the minimum of the other weeks are added.
(b) The differences in the amount of global radiation, dry bulb temperature and wind speed for each of the above instances are added separately for those above the maximum or below the maximum values.

By detailed comparisons of the referred parameters, any unusual traits in the day of the week for each hour could be detected. Thus, two typical weeks (18th–24th May and 18th–24th October) are selected for long-term indoor thermal comfort evaluation. The percentage of hours within the thermal comfort zone in each typical week is taken as the criteria for facade design evaluation.

In the parametric study, the combination effects of several facade design parameters in naturally ventilated buildings, including four different orientations (north, south, west and east), three various window to wall ratios

(0.12, 0.24 and 0.3) and three horizontal shading dimensions (0, 600, 900 mm), are taking into considerations. The window to wall ratio in kitchen room is the same as the one in the investigated living room. Concrete hollow block wall, which is widely used in building construction in Singapore, is taken as both external and internal wall materials in the building. Thermal transmittance of the 100 mm concrete hollow block wall is 1.89 $W/m^2 K$. Indoor heat sources including equipments, lighting, and occupants are negligible in the unit. In total, 26 various facade design scenarios were investigated and 52 cases were simulated for indoor thermal comfort evaluation for the two typical weeks in dry and raining seasons.

A series of coupled simulations are carried out for 26 facade design options. Coupled simulations for each particular facade design is performed for two typical weeks (18th–24th May and 18th–24th October), and the simulation results for each case are analyzed based on thermal comfort index (Eq. (1)) and represented by thermal comfort percentage in both typical weeks.

The simulation results for thermal comfort percentage in the typical weeks are shown in Tables 2–5 for four different orientations. It can be seen from the results that south- and north-facing units have much better indoor thermal environment than east- and west-facing units in Singapore. The results also show that the thermal comfort conditions in raining season are much better those in the dry season. This can be attributed to two reasons: the ambient temperatures in the raining season are normally lower than those in the dry season; and solar heat gains in the raining season are less since the raining season happens in the winter time.

Table 2
Thermal comfort percentage in two typical weeks in North orientation

WWR	Shading	Thermal comfort percentage	
		Typical week in May	Typical week in October
0.121	0	52.98	80.23
0.121	600	55.95	80.95
0.24	0	66.07	88.09
0.24	600	70.8	88.09
0.3	0	66.67	88.09
0.3	600	72.02	88.09

Table 3
Thermal comfort percentage in two typical weeks in South orientation

WWR	Shading	Thermal comfort percentage	
		Typical week in May	Typical week in October
0.121	0	72.62	81.54
0.121	600	72.62	83.33
0.24	0	78.57	83.90
0.24	600	78.57	86.90
0.3	0	77.97	84.52
0.3	600	77.97	86.90

Table 4
Thermal comfort percentage in two typical weeks in East orientation

WWR	Shading	Thermal comfort percentage	
		Typical week in May	Typical week in October
0.121	0	52.97	54.16
0.121	600	55.35	56.28
0.24	0	64.88	69.04
0.24	600	66.07	70.24
0.3	0	64.88	69.04
0.3	600	66.07	69.60
0.3	900	66.07	70.24

Table 5
Thermal comfort percentage in two typical weeks in West orientation

WWR	Shading	Thermal comfort percentage	
		Typical week in May	Typical week in October
0.121	0	46.42	57.14
0.121	600	46.42	58.93
0.24	0	53.57	62.27
0.24	600	54.17	64.28
0.3	0	53.57	63.09
0.3	600	54.17	63.09
0.3	900	55.35	63.09

As can be seen from the results (Table 2) in May, indoor thermal comfort environment can be largely improved by 13% with the increase of window to wall size from 0.12 to 0.24 and indoor satisfactory thermal comfort percentage is improved when shading device is added. However, when the window to wall ratio is further increased to 0.3, there is no obvious improvement in thermal conditions when shading device is not added. This probably indicates that the increased indoor air velocity with the increase of window to wall ratios cannot compensate, or just compensate, the indoor temperature increases with the increase of heat gains. That is to say, the increase of window to wall ratios would increase indoor air velocity on the one hand, but would increase the indoor air temperature on the other hand since more heat gains from solar radiation and ambient could be induced from the larger openings. Therefore, as we can see from the results, with the 600 mm horizontal shading devices above the window, indoor thermal comfort environment could be further improved. For the thermal conditions in October (rainy season), the effects of shading device on thermal comfort are not obvious.

Thermal comfort percentage in south orientation is shown in Table 3. Thermal comfort conditions for south-facing room are generally good in both dry and raining seasons. There is an obvious improvement in thermal comfort when the window to wall ratios has been increased to 0.24 and 600 mm horizontal shading device are needed for better thermal comfort when solar is in the south hemisphere.

Tables 4 and 5 illustrate the results of thermal comfort percentage for east and west orientations, respectively. Compared with the other two orientations, satisfactory thermal comfort percentages in the two typical weeks for east- and west-facing room are much lower. Same as north and south orientations, the increase of window to wall ratios to 0.24 can largely improve indoor thermal comfort by increasing indoor air velocity. Horizontal shading device are needed for both orientations to further improve the indoor thermal comfort. However, with the increase of the length of shading device to 900 mm, thermal comfort percentage in the typical week in May for west orientation is still not satisfactory enough to meet thermal comfort requirements in most of the time. Under this condition, mechanical ventilation may probably be used to improve indoor thermal comfort. Thus, east- or west-facing rooms should be avoided for residential buildings for the purpose of thermal comfort and energy consumption in Singapore. By any means, the improvement of facade designs in naturally ventilated buildings can largely alleviate the burden of energy crises and provide us a natural and comfortable indoor environment.

6. Conclusions

Based on the above investigations of natural ventilation in Singapore, the following significant results are generated.

(1) With the investigation on natural ventilation strategies, it is proved that full-day ventilation can provide better thermal comfort for hot-humid climate in Singapore.
(2) The results indicate that non-insulated construction materials with thermal mass inertia are ideal choice for naturally ventilated buildings in hot-humid climate.
(3) North- and south-facing facades can provide much comfortable indoor environment than east- and west-facing facades in Singapore. The closed window for daylighting on east and west orientations should be avoided in the designs of naturally ventilated buildings for better indoor thermal environment.
(4) The increase of window to wall ratio to 0.24 can improve indoor thermal conditions to a large extent and horizontal shading devices are needed for the four orientations for further improvement in indoor thermal comfort. In the future studies, other shade devices like vertical fins or the combination of both vertical fins and horizontal shading devices could be investigated on west- and east-facing facade in order to provide better indoor thermal comfort.

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